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Implementation of Quadrupole Scan Technique for Transverse Beam Emittance Measurements at Fermilab's Advanced Superconducting Test Accelerator (ASTA)

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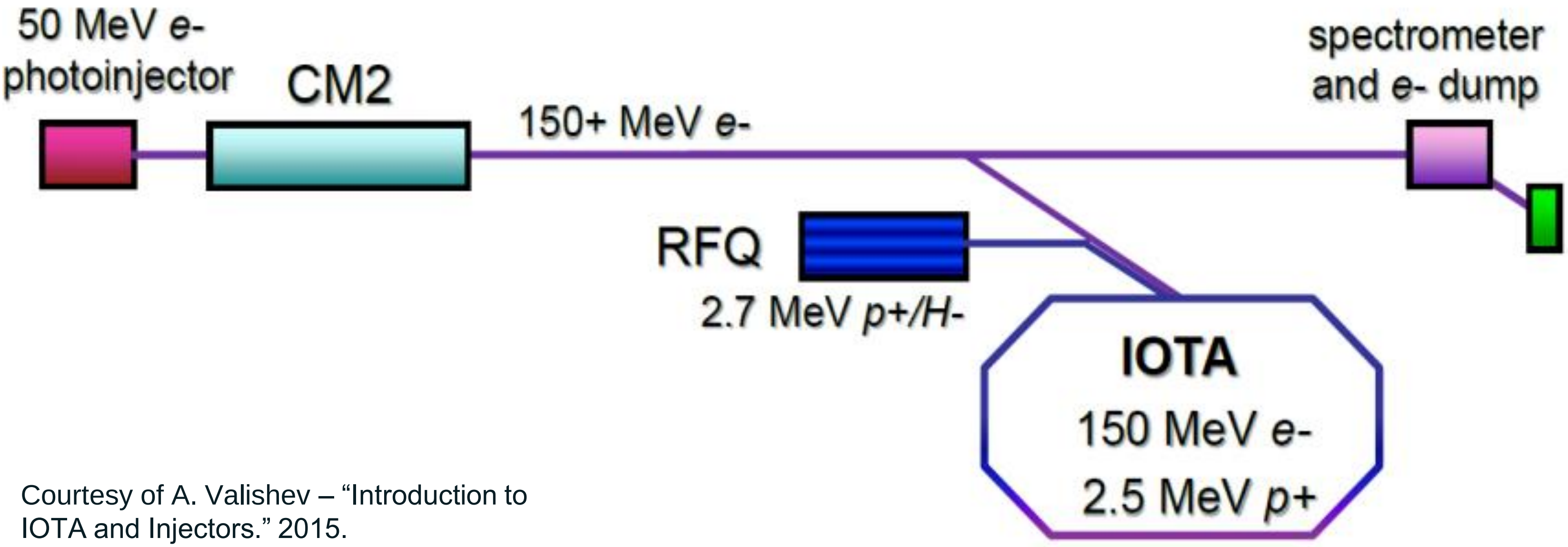
Introduction

- ASTA
- What is beam emittance?
- Quadrupole magnets and the “thin lens” approximation.
- Quadrupole scan technique.
- Simulated & preliminary experimental results.
- Automation.

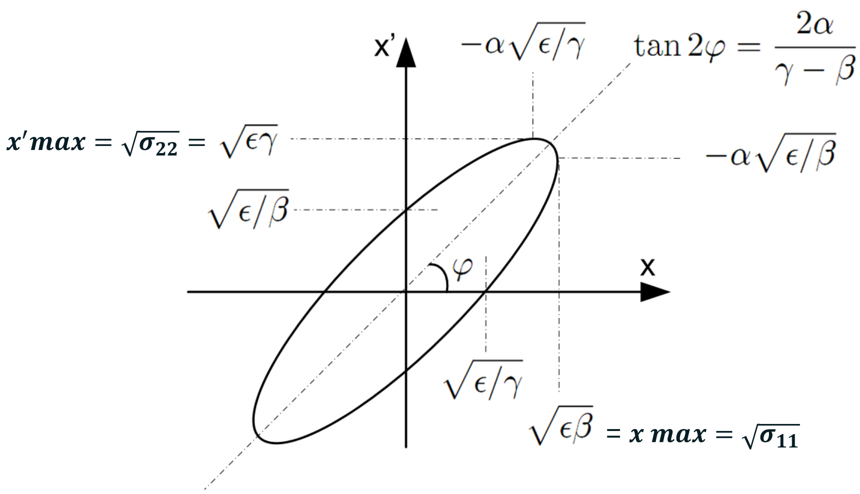
Parameter	ILC nominal	Range
Bunch charge	3.2 nC	10pC to > 20 nC
Bunch spacing	333 ns	<10 ns to 10 s
Bunch train	1 ms	1 bunch to 1 ms
Train rep. rate	5 Hz	0.1 Hz to 5 Hz
Transverse emit.	25 mm-mrad	1 to 100 mm-mrad
r.m.s. bunch length	1 ps	10fs to 10ps
Beam energy	300 MeV	50-300 MeV



Courtesy of A. Valishev – “Introduction to IOTA and Injectors.” 2015.

Beam Emittance

- Emittance is an important characteristic of charged particle beams (describes the quality of a beam).
- 6-D phase space (x, p_x, y, p_y, z, p_z) → three 2-D phase spaces → three 2-D trace spaces (x, x'), (y, y'), and (z, z').



Emmanuel Branlard - http://emmanuel.branlard.free.fr/work/papers/html/2009fermi/node18

- The particles of interest can be thought of as being bound by an ellipse and defined by a symmetric moment matrix.

$$\sigma(z) = \begin{vmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{vmatrix}$$

- Liouville's Theorem: area of the ellipse is a conserved quantity.
- Under boosts, only normalized emittance (ϵ_n) is conserved.
- Geometrical emittance:

$$\begin{aligned} \epsilon_x &= \pi \cdot Area \\ &= \gamma x^2 + 2\alpha x x' + \beta x'^2 \\ &= \pi \cdot \sqrt{\det(\sigma_x)} \end{aligned}$$

- Normalized emittance: $\epsilon_{n_x} = \beta\gamma\epsilon_x$

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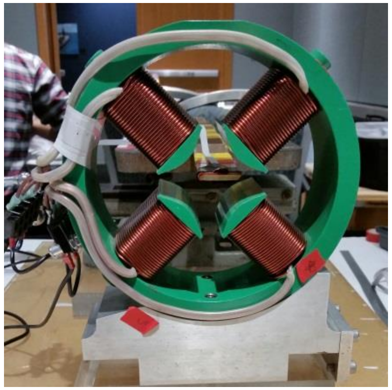
Quadrupole Magnets

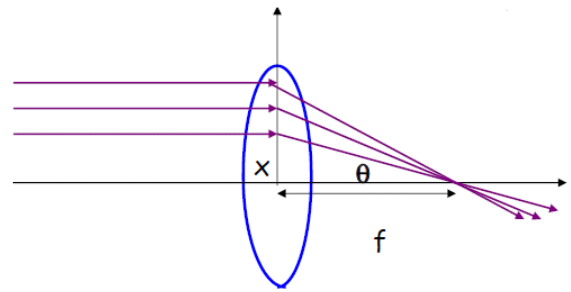


- B-field is zero at the center of the quad and increases as you approach the poles.

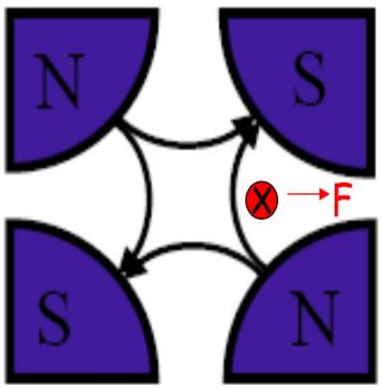
- From Maxwell's equations:

$$B' = \frac{dB_\phi}{dr} = \frac{8\pi I}{cR^2}$$

Optical Lens



"Magnetic Fields and Magnet Design" – J. Holmes, S. Henderson, Y. Zhang. USPAS. Jan., 2009.

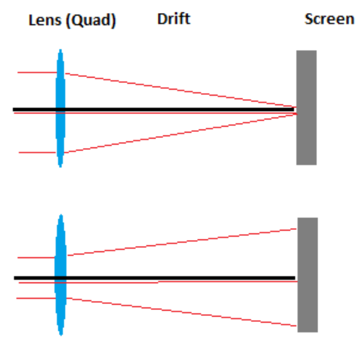


"Magnetic Fields and Magnet Design" – J. Holmes, S. Henderson, Y. Zhang. USPAS. Jan., 2009.

- Optical Lens: rays of light come to a focus at the focal point. The farther off the axis, the stronger the focusing.

- Magnetic Lens: particles in the beam are given a momentum kick. Focus in one plane, defocus in the other.

Magnetic Lens



"Magnetic Fields and Magnet Design" – J. Holmes, S. Henderson, Y. Zhang. USPAS. Jan., 2009.

Lorentz Force and RHR:

$$F = q[E + (v \times B)]$$

- Positive particle moving into the page would be deflected to the right.

$$\frac{1}{f} = \frac{e}{pc} gL = \frac{gL}{B\rho}, \text{ where } g = \frac{dB_y}{dx}$$

$$k[\text{m}^{-2}] = \frac{1}{fL} = \frac{e}{pc} g = \frac{0.299\, g[\text{T/m}]}{\beta E[\text{GeV}]} = \text{focusing strength}$$

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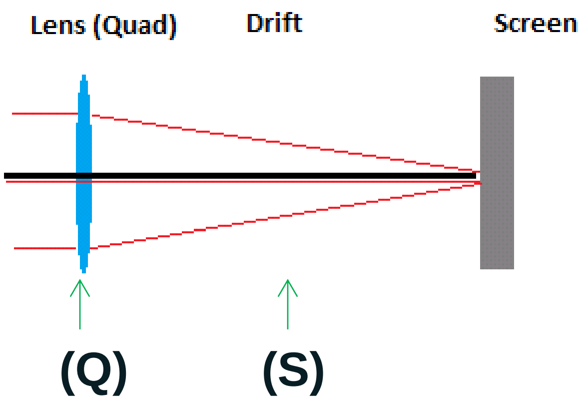
“Thin Lens” Approximation



“Thick Lens” Model:

$$Q_x = \begin{vmatrix} cos\phi & \frac{1}{\sqrt{|k|}} sin\phi \\ \sqrt{|k|} sin\phi & cos\phi \end{vmatrix} \qquad \left[\phi = l\sqrt{|k|}\right]$$

$$Q_y = \begin{vmatrix} cosh\phi & \frac{1}{\sqrt{|k|}} sinh\phi \\ -\sqrt{|k|} sinh\phi & cosh\phi \end{vmatrix}$$

$$S = \begin{vmatrix} 1 & L \\ 0 & 1 \end{vmatrix}$$

Transfer matrix: $R = SQ$ → $\Sigma_f = R\Sigma_i R^T$

“Thin Lens” Approximation:

- “Thin lens” approximation treats the quad length as zero, while holding the focal length constant.
- $\frac{1}{f} = k \cdot l$, where k is the quad field strength and l is the effective quad length.
- When k is negative → focusing quad.
- When k is positive → defocusing quad.

$$Q_x = \begin{vmatrix} 1 & 0 \\ kl & 1 \end{vmatrix}$$

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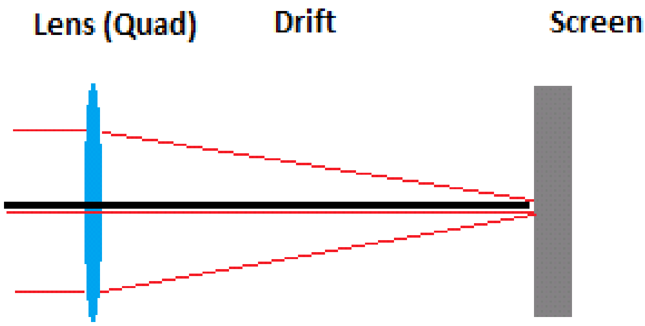
Quadrupole Scan

1. Select a single quadrupole magnet and an imaging screen (typically a YAG or OTR screen).

2. 'Scan' the magnet by varying the quad field strength and measure the rms beam size on the screen.



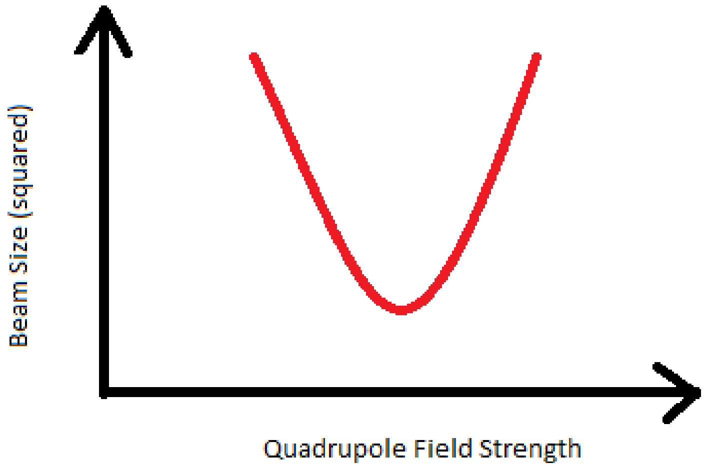
Emittance Calculation

- Plot - $beam\ size^2\ vs.\ quad\ field\ strength$.

- Apply a 2nd order polynomial fit to the curve to get three coefficients: $\Sigma_{11} = Ak^2 + Bk + C$

- Using the coefficients, you can calculate the beam matrix elements.

- From the beam matrix (Σ_{beam}), calculate the emittance and C-S parameters.



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- Quadrupole focusing strength is controlled by power supplies via the ACNET console.
- Focus the beam.
- Find the minimum spot size.
- Scan the quad by varying the current.
- Record the rms beamsize, via Gaussian fit, on a YAG screen (measured in μm or pixels).

Fig.1: Beam with default quad settings (beam size $< 3\ mm$.).

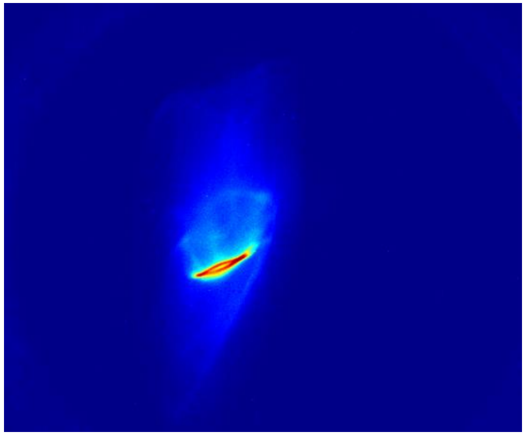
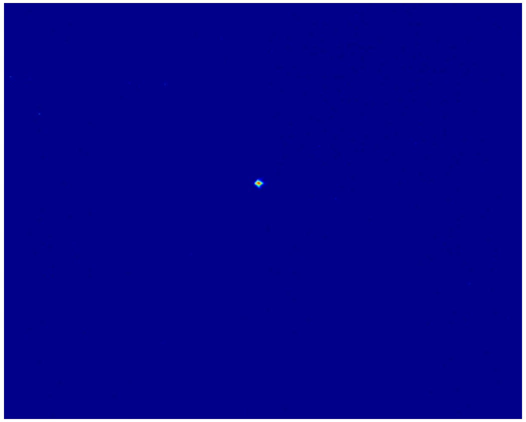
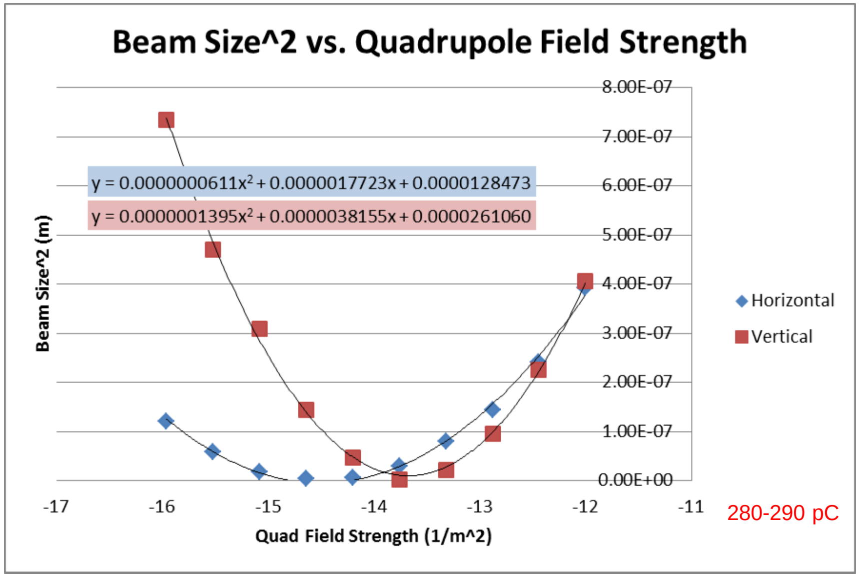


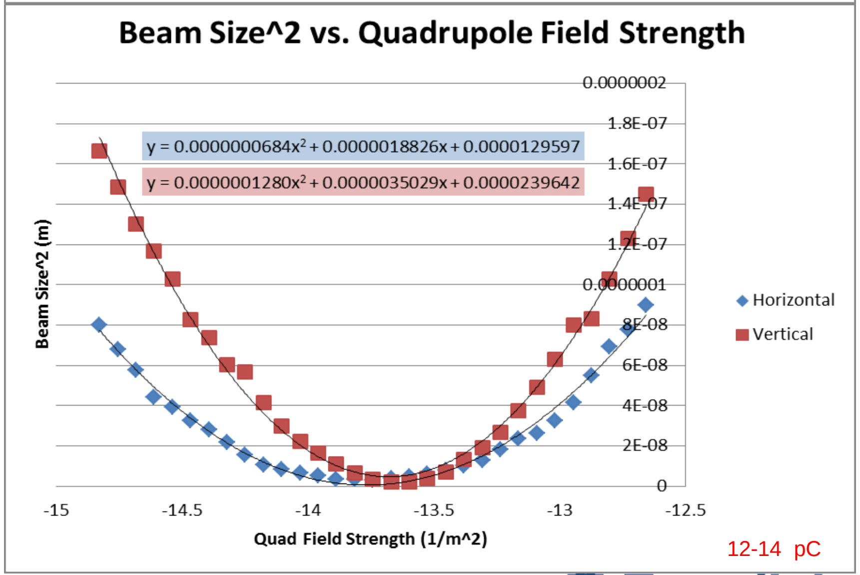
Fig.2: Focused beam (beam size $< 100\ \mu m$).



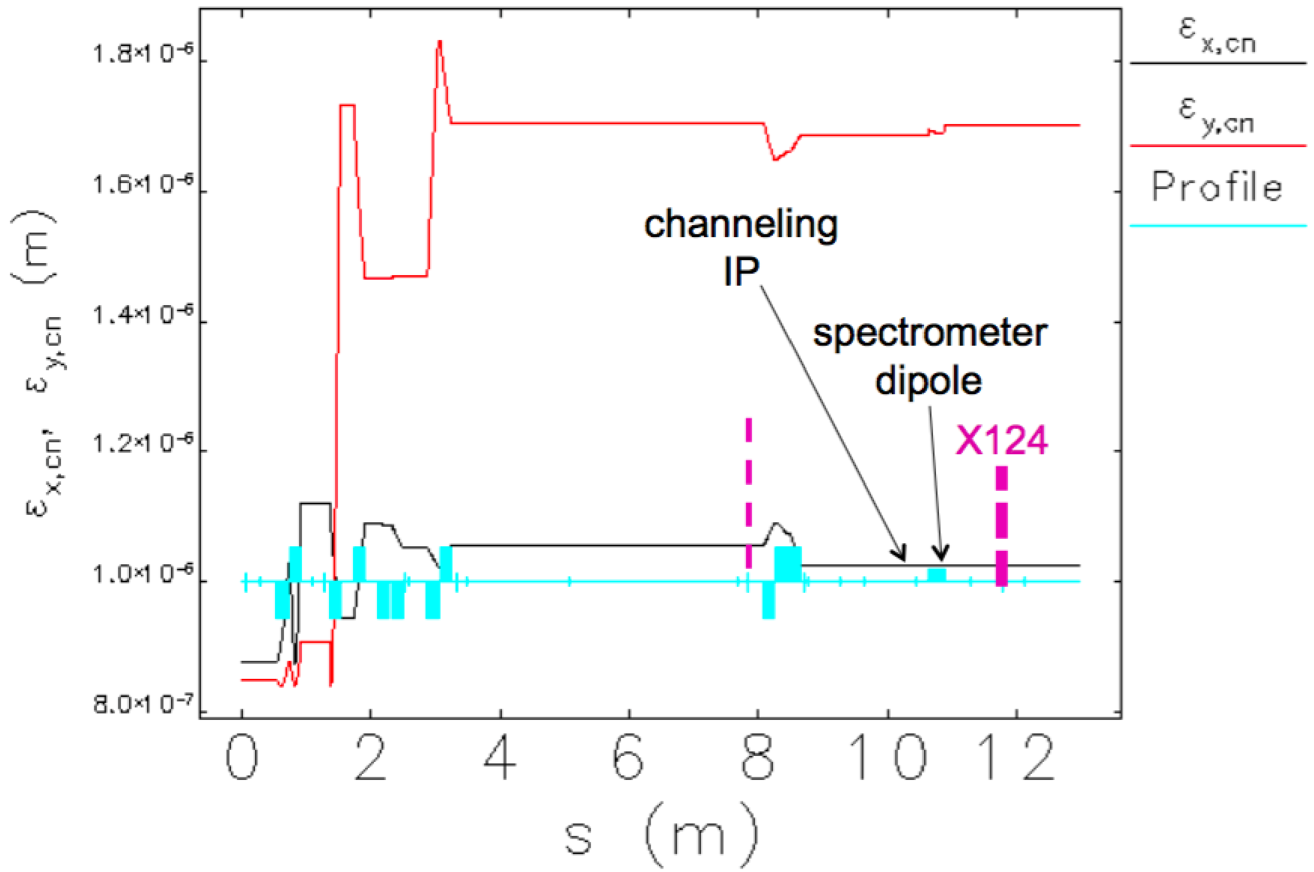
Preliminary Experimental Results

Parameter	Value
Beam Energy	$\sim 20\ MeV$
Bunch Charge	$280-290\ pC$
α_x/α_y	$-33.292/25.782$
β_x/β_y	$21.605/18.349$
$\epsilon_{n_x}/\epsilon_{n_y}$	$2.95\ mm \cdot mrad/8.14\ mm \cdot mrad$
Beam Energy	$\sim 20\ MeV$
Bunch Charge	$12-14\ pC$
α_x/α_y	$-45.172/45.071$
β_x/β_y	$31.985/32.185$
$\epsilon_{n_x}/\epsilon_{n_y}$	$2.05\ mm \cdot mrad/5.06\ mm \cdot mrad$





Emittance evolution downstream of CAV2



"Possible 1st-beam lattice steup(s) with one cavity" – P.R.G. Piot, IOTA/ASTA User's Meeting, Jan. 2015

Tuning

- Accelerator is still in the commissioning stage and not yet complete.
- Beamline is not fully tuned for optimization.

Thin Lens vs. Thick Lens

- We are currently using the “thin lens” approximation.
- “Thick lens” model will yield more accurate results.

- Preliminary version of automated quad scan used last week:
  - Written in Python.
  - Decreased quad scan time from $\sim 2hr$ to less than $10min$.

- Preliminary version of emittance and C-S parameter calculator written in Python:
  - Enter quad field range and beam parameters.
  - Displays plots, polyfit, geometrical and normalized transverse emittance, C-S parameters.

Summary

- ASTA injector/superconducting linac built for high level accelerator R&D.
- Emittance measurements are important for high quality beams.
- Measurements have been taken and are currently being analyzed.
- Shift from “thin lens” approximation to “thick lens” model.
- Further tuning and optimization needed.
- Simple and time saving automated quad scans have been successful.
- Full implementation of automated quad scan/emittance measurements.

Special thank you to the ASTA operators: Chip Edstrom, Jinhao Ruan, and Darren Crawford

Also, a special thank you to the following for technical discussions and support: Dan Broemmelsiek, Alex Lumpkin, Jamie Santucci, Charles Thangaraj, Giulio Stancari, Sasha Valishev, Philippe Piot, and Young-Min Shin.

References

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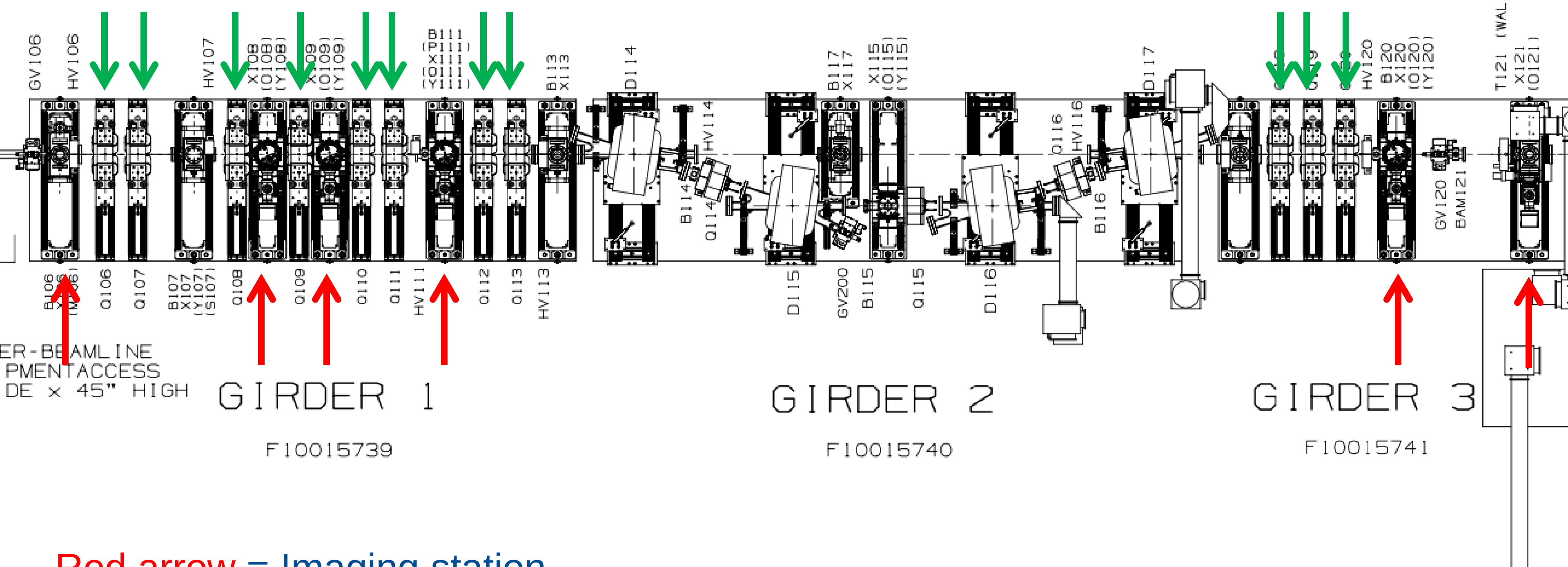
Extra Slides

ASTA Quads/Imaging Screens



Red arrow = Imaging station

Green arrow = Quadrupole magnet

"Thin Lens" Approximation

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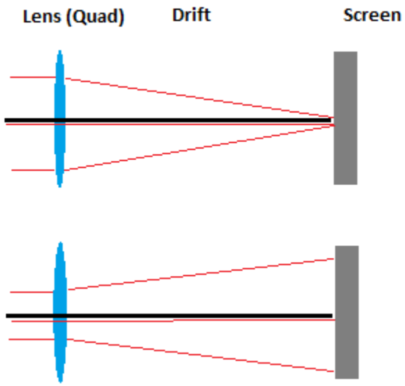

Transfer Matrix

$$R = SQ = \begin{vmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{vmatrix} \cdot \begin{vmatrix} 1 & 0 \\ kl & 1 \end{vmatrix}$$

Solving for emittance

$$\Sigma_{11} = \langle x_f^2 \rangle = (S_{11} + klS_{12})^2 \langle x_i^2 \rangle + S_{12}^2 \langle x_i'^2 \rangle + 2S_{12}(S_{11} + klS_{12}) \langle x_i x_i' \rangle$$

$$\Sigma_{11} = Ak^2 + Bk + C$$

$$\Sigma_{11} = \frac{A}{l^2 \cdot S_{12}^2} \qquad \alpha = -\frac{\Sigma_{12}}{\epsilon}$$

$$\Sigma_{12} = \Sigma_{21} = \frac{B - 2\Sigma_{11} \cdot l \cdot S_{11} \cdot S_{12}}{2l \cdot S_{12}^2} \qquad \beta = \frac{\Sigma_{11}}{\epsilon}$$

$$\Sigma_{22} = \frac{C - \Sigma_{11} \cdot S_{11}^2 - 2\Sigma_{12} \cdot S_{11} \cdot S_{12}}{S_{12}^2} \qquad \gamma = \frac{\Sigma_{22}}{\epsilon}$$